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New insight on the stratigraphy of the "Upper Thamama" in offshore Abu Dhabi (U.A.E.)

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Abstract: An integrated case study of field "A" in offshore Abu Dhabi found that the stratigraphic framework for the uppermost part of the so-called "Thamama Group" required revision. Detailed sedimentological work permitted a subdivision of the succession into lithostratigraphic units (more accurately "allostratigraphic units") and the fossil content permitted their allocation to standard age-related units ranging from Late Barremian through Middle Aptian times. Additional work focused on the so-called "Shu'aiba Formation" and resulted in a new and comprehensive interpretation on a regional scale which differs from published interpretations based on onshore studies in Abu Dhabi, Qatar, and Oman.

Key Words: Allostratigraphy, lithostratigraphy, Cretaceous, Hauterivian, Barremian, Aptian, Bedoulian, Gargasian, Clansayesian, Albian, Lekhwair, Hawar, Shu'aiba, Bab, Sabsab, Nahr Umr, Abu Dhabi, Iraq, Qatar, Oman

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Résumé : Nouvel aperçu de la stratigraphie du "Thamama supérieur" dans le domaine maritime d'Abou Dabi (Émirats Arabes Unis).- Le découpage stratigraphique de la partie supérieure du "Thamama" dans le domaine maritime d'Abou Dabi nécessitait une révision significative comme cela est démontré avec l'étude intégrée du champ "A". Un travail de détail en sédimentologie a permis de subdiviser cette partie de la série en unités lithostratigraphiques (notons toutefois que le vocable "allostratigraphiques" serait plus précis pour définir ce type de catégories stratigraphiques) alors que la paléontologie permettait leur calage chronostratigraphique dans l'intervalle Barrémien supérieur-Aptien moyen. Un travail complémentaire focalisé sur le "Shu'aiba" a abouti à l'établissement d'une interprétation différente de celles antérieurement publiées qui se basaient sur le domaine continental d'Abou Dabi, ainsi que sur le Qatar ou l'Oman, et qu'il est également possible d'étendre à l'échelle régionale.

Mots-Clefs : Allostratigraphie, lithostratigraphie, Crétacé, Hauterivien, Barrémien, Aptien, Bédoulien, Gargasien, Clansayésien, Albien, Lekhwair, Hawar, Shu'aiba, Bab, Sabsab, Nahr Umr, Abu Dhabi, Iraq, Qatar, Oman

Introduction

In the offshore areas of Abu Dhabi (Fig. 1) the "Thamama Group" includes the uppermost part of the Sahtan Supersynthem (pro "Group"), the whole of the Kahmah Supersynthem (pro

"Group"), and the lowermost part of the Wasi'a Supersynthem (pro "Group"). The upper portion incorporates the Kharaib, Hawar, Shu'aiba, Bab, and Sabsab synthems (pro "formations"); the respective underlying and overlying units are the Lekhwair and Nahr Umr synthems (pro "formations"). All of these entities were defined

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from subsurface data and were correlated more or less successfully throughout the whole of the southeastern Arabian Gulf oil province (Fig. 2). Such operational rock subdivisions were not considered valid lithostratigraphic units until it was recently demonstrated (GRANIER, 2000) that they fall into the category of "unconformity-bounded units" (SALVADOR, 1987; also known as "allostratigraphic units"). The surfaces bounding these units are for the most part, but not always, transgressive surfaces (TS) that are often but not always coincident with sequence boundaries (SB). Such surfaces are used to obtain precise stratigraphic correlations between wells in the Abu Dhabi offshore.

To date approximately 4,000 feet of cores have been recovered from 16 of the 43 wells drilled in field "A" in offshore Abu Dhabi. This study documents most of the third order tectono-eustatic cycles that occurred in Barremian through Aptian times. The related stratigraphic sequences and their bounding surfaces provide the elements for the establishment of comprehensive geological models as demonstrated below for the "Shu'aiba".

Historical background

Lithostratigraphy

The lithostratigraphic framework used in the onshore and offshore areas of Abu Dhabi (Fig. 1) was issued by HASSAN, MUDD and TWOMBLEY (1975) who followed the recommendations of the "Geological Liaison Committee" formed by several companies operating in Abu Dhabi, Dubai, Oman, Qatar, and Sharjah, *i.e.* in the southeastern Arabian Gulf oil province.

The **Lekhwait Formation** was first mentioned by SCHERER (1969, unpublished report) but it was published only in 1975 by HASSAN, MUDD and TWOMBLEY. Though the type section was originally chosen in PDO well Lekhwait N° 6 in western Oman, according to HUGHES CLARKE (1988), well N° 7 should have been selected.

The **Kharaib and Hawar formations** were first mentioned by SUGDEN (1953, unpublished report), but were not published until 1975 by SUGDEN and STANDRING. The type sections of both formations are in QGPC (ex QPC) well Kharaib N° 1 in central Qatar. In Oman the Hawar Formation has been lumped with the overlying Shu'aiba Formation and in Abu Dhabi with the underlying Kharaib Formation.



Figure 1: Location map of United Arab Emirates and its major oil fields.

The **Shu'aiba Formation** was first mentioned by RABANIT (1951, unpublished report), but was not published until 1958 by OWEN and NASR. The formation was subsequently redefined by DUNNINGTON, WETZEL and MORTON (1959) who reverted to the original, unpublished description by RABANIT; and by AL NAQIB (1967) who chose to lower the top of the formation considerably. The type section of the Shu'aiba Formation (Fig. 3) is in INOC (ex BPC) well Zubair N° 3 in southern Iraq. In most Abu Dhabi offshore areas the Shu'aiba Formation has been split into local sub-units. The upper sub-unit consists of basin deposits with "Globigerinids" and it has been referred to as the "**Bab Member**" by HASSAN, MUDD and TWOMBLY (1975). The type section of the Bab Member (Fig. 4) is in ADCO (ex ADPC) well Murban N° 2 in onshore Abu Dhabi. In later discussions of this unit (AL NAQIB, 1967), the type Shu'aiba does not include the "Globigerinid" facies. Consequently the Bab "Member" was upgraded to formational rank

(GRANIER, 2000). Moreover, the base of the type section of the Shu'aiba Formation still included a time equivalent of the Hawar Formation; therefore the lower boundary of the Shu'aiba Formation should be raised to exclude the basal 7 foot "pseudo-oolitic limestone" with "*Orbitolina discoidea*" (RABANIT, 1951, unpublished report) as well as the thin shaly layer immediately overlying it (GRANIER, 2000).

The **Sabsab Formation** is an informal lithostratigraphic unit (Fig. 5-6), which was first published by SUGDEN and STANDRING (1975). The type section of the formation is in QGPC (ex QPC) well Dukhan N° 27 in western Qatar. It was described as an oolitic, pellety limestone containing abundant abraded orbitolinids. It was erroneously believed to be channel infills.

The **Nahr Umr Formation** was first mentioned by GLYNN JONES (1948, unpublished report), and was published by OWEN and NASR (1958). The type section is in the INOC (ex BPC) well Nahr Umr N° 2 in southern Iraq.

Reservoir zones and sub-zones (ADMA)		Reservoir sub-zone (ADCO): Bu Hasa		Azer & Toland	Boichard et alii	Russell et alii	van Buchem et alii		This work	Synthem	Super-synthem
		S	N				2nd order	3rd order	...	NAHR UMR	
THAMAMA I		I > (*)	H pars, G, Bab	HST	TST	TST		HST	TST	SABSAB	WASI'A
				LST	LST	LST		TST	HST		
				HST				TST	HST		
				TST	TST		HST	HST	LST 1		
									HST		
THAMAMA II	I-A	I < (**)	A-B, D, F	HST	LST	HST		TST	TST	SH'UAIBA	KHAMAH
				HST	HST	TST		HST			
						HST					
				TST	TST	TST		TST	HST	HAWAR	
THAMAMA III	II	B		HST	HST		HST		HST 4		
									TST 4		
									HST 3		
				TST	TST		TST		TST 3		
									HST 2		
THAMAMA III	III-A	C		HST	HST		HST		TST 2		
									HST 1		
									TST 1		
							TST		...	LEKHWAIR	

* the Orbitolinid-rich layer and above

** missing section in the southern part of Bu Hasa field

*** below the Orbitolinid-rich layer

Figure 2: The relationship of the main reservoir zones to the sequence stratigraphic subdivisions of the upper part of the so-called "Thamama".

Biostratigraphy

Microfossils

Microfossils reported by BANNER and WOOD (1964), and by HASSAN, MUDD and TWOMBLY (1975) refer to obsolete names, such as "*Orbitolina* cf. *discoidea* GRAS" which presumably include several taxa belonging either to the genus *Eopalarbitolina* or to the genus *Palorbitolina*. The same authors also quoted long-ranging species, like *Choffatella decipiens* (Hauterivian-Aptian), *Dictyoconus arabicus* (Barremian-Early Aptian; it is now assigned to the genus *Montseciella* CHERCHI et SCHROEDER 1999[b]), and *Salpingoporella*

(*Hensonella*) *dinarica* (Tithonian - Aptian, according to GRANIER, 2002).

Based on an assemblage of non-coeval species (according to SCHROEDER *et alii*, 2002) including *Eopalarbitolina charollaisi* (Hauterivian 7-Barremian 2), *Valserina broennimanni* (Hauterivian 7-Barremian 1), *Dictyorbitolina ichnusae* (Hauterivian 7-Barremian 2), and *Palorbitolina lenticularis* (Barremian 4-Bedoulian 4), AZER and TOLAND (1993) assign a Barremian age to the base of the Kharaib Formation; this dating and additional fossil identifications, such as "*Pseudocyclamina litus*" (*sic*) for instance, are open to question.

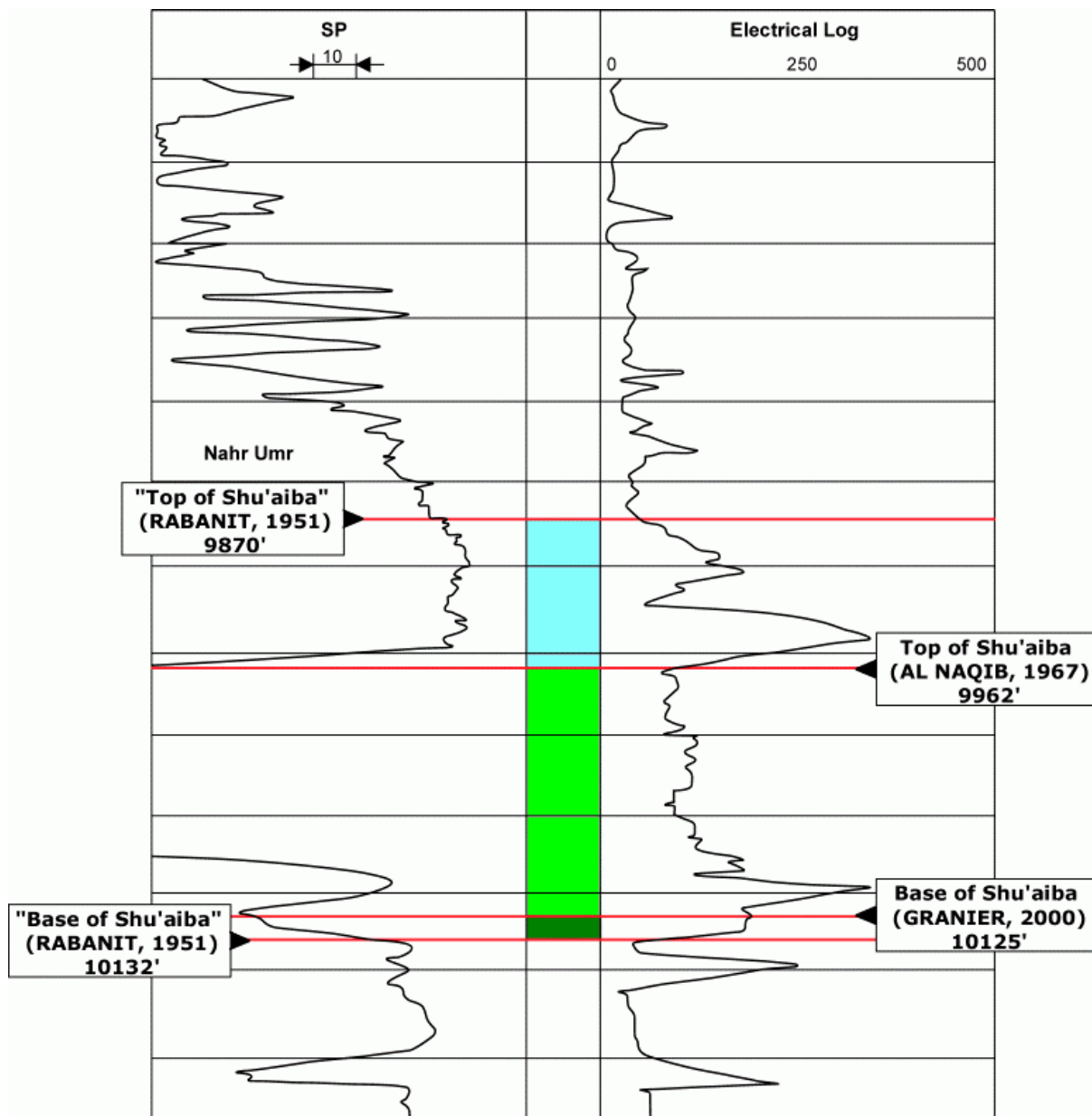


Figure 3: Type section of the Shu'aiba Formation from RABANIT (1951, unpublished report), modified by AL NAQIB (1967) and GRANIER (2000): INOC (ex BPC) well Zubair N° 3 in southern Iraq.

Ammonites

In some Abu Dhabi wells, core samples from the uppermost part of the studied interval (*i.e.* the uppermost Shu'aiba and most of the Bab) include ammonites. Most of the citations listed below seem credible though they are not substantiated by figured specimens nor accompanied by any indication of where the original samples are stored. In the offshore area, specimens identified by WRIGHT (1959, unpublished report; BANNER and WOOD, 1964; HASSAN, MUDD and TWOMBLY, 1975; AZER and TOLAND, 1993) from "Umm Shaif well N° 2" comprise *Chelonicer* (*Epicheloniceras*) sp., *Colombiceras* cf. *caucasicum*, and an ancyloceratinid form. Those identified by HOWARTH (1992, unpublished report; AZER and TOLAND, 1993) from "Umm Shaif well N° 3" include cf. *Pseudohaploceras* sp. and *Diadochoceras* sp. In addition, HASSAN, MUDD and TWOMBLY (1975) reported *Pseudosaynella fimbriata*, *Pseudohaploceras* sp., *Diadochoceras* sp., *Gargasicer* sp., and *Dufrenoyia* sp., possibly from ADCO well Murban N° 2 in the onshore. These findings indicate a Middle Aptian (Gargasian) age.

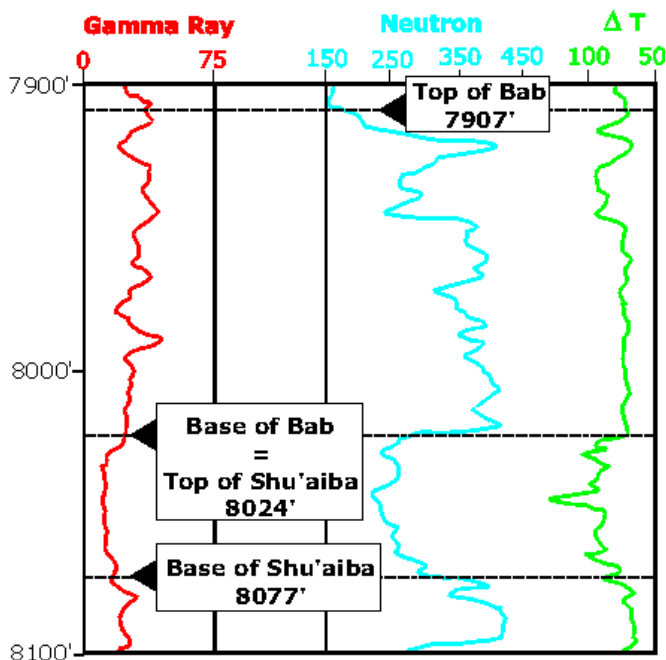


Figure 4: Type section of the Bab Formation from CALAVAN *et alii* (1992): ADCO (ex ADPC) well Murban N° 2 in onshore Abu Dhabi.

Sequence stratigraphy

The sequence stratigraphy of the Upper Thamama by AZER and TOLAND (1993) was based on three offshore wells ("Umm Shaif N° 88, Zakum N° 182, and Umm Lulu N° 3"). BOICHARD, AL-SUWAIDI and KARAKHANIAN (1994) published another version for the Upper Thamama based on data from field "A". Though there was some agreement on subdivision of the Kharai Formation, these opinions diverged significantly

when dealing with the Shu'aiba Formation. Although both schemes included the Bab Member, AZER and TOLAND (1993) identified two sequences therein, while BOICHARD, AL-SUWAIDI and KARAKHANIAN (1994) found three.

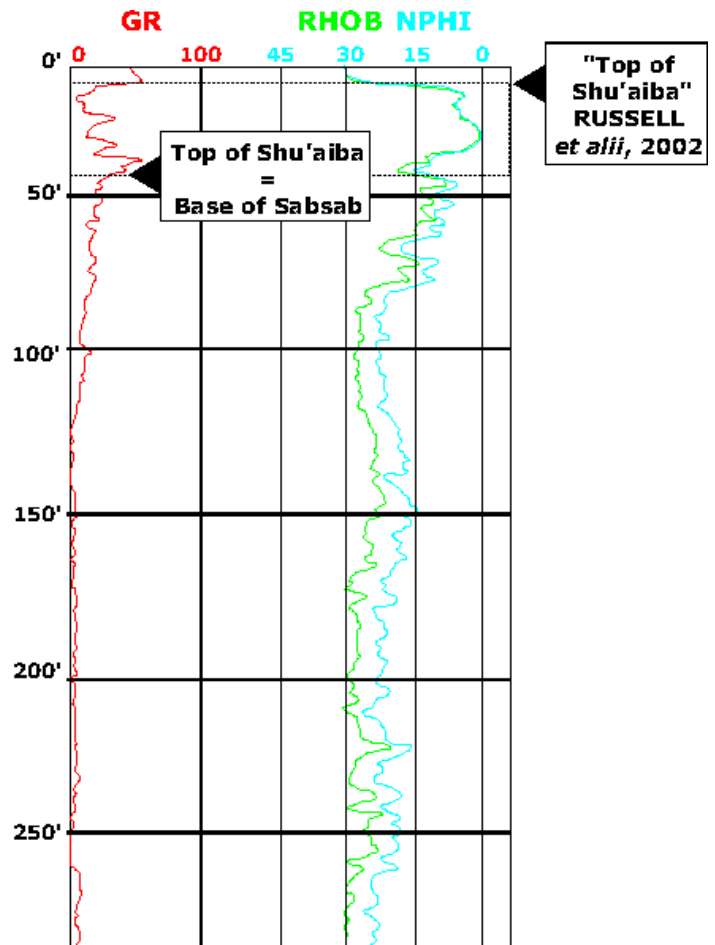


Figure 5: Example of the Shu'aiba - Sabsab boundary (here a karst surface and/or an erosional surface) in a platform setting: South Bu Hasa well N° A in onshore Abu Dhabi from RUSSELL *et alii* (2002), modified.

Allostratigraphy

In his 2000 paper, GRANIER applied this new stratigraphic classification to the operational units documented in the offshore of Abu Dhabi. The so-called "Thamama Group" covers 9 synthems (*i.e.* alloformations) which are from top to bottom: Bab, Shu'aiba, Hawar, Kharai, Lekhwair, Zakum, Belbazem, Bu Haseer, and Habshan. This new classification, which is based on 'unconformity-bounded units', is supported by both biostratigraphic data and sequence stratigraphy. This revised stratigraphic framework suggests that a new interpretation of regional basinal history is necessary.

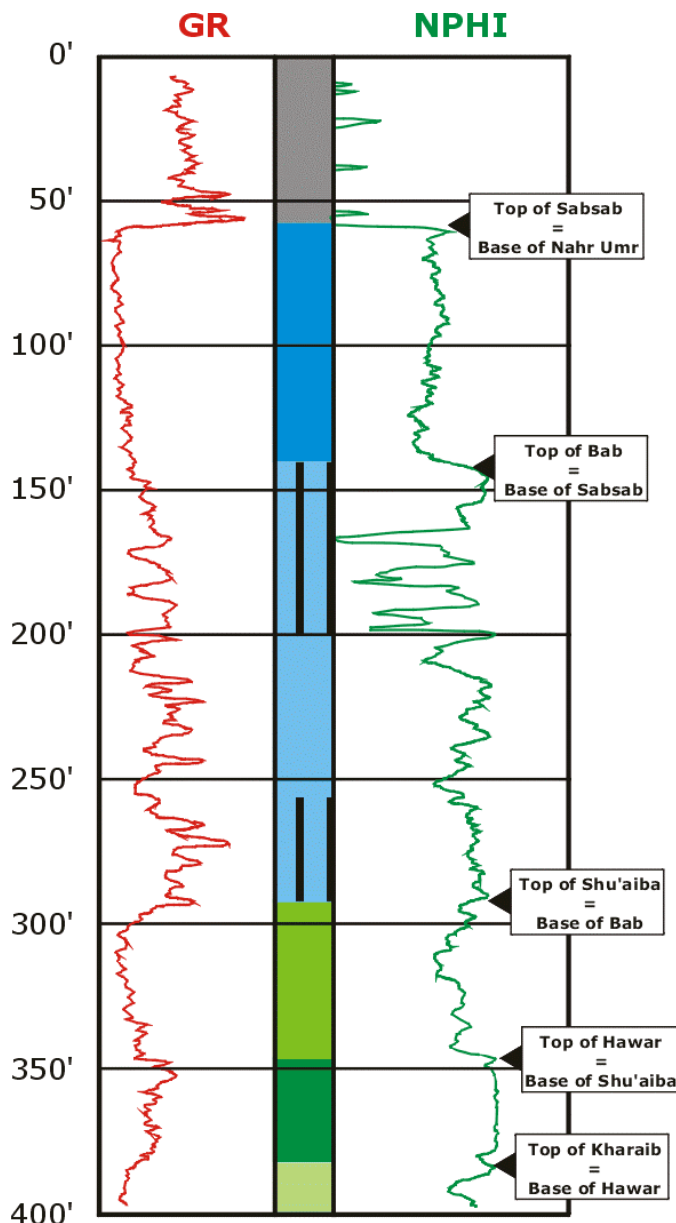


Figure 6: Example of both Shu'aiba - Bab and Bab - Sabsab boundaries in a basinal setting: ADMA well N° 4 of field "B", offshore Abu Dhabi.

Although other interpretations have been proposed recently: SHARLAND *et alii* (2001), VAN BUCHEM *et alii* (2002), RUSSELL *et alii* (2002), DAVIES *et alii* (2002), none are supported by fresh paleontological findings.

Reframing the "Upper Thamama"

Based on detailed sedimentological and micropaleontological investigations of the wells in "A" field, we propose here a new version of the sequence stratigraphy for the upper part of the Thamama Group.

In the next section, numbers in brackets refer to vertical thicknesses as recorded in the reference well in field "A" (Fig. 7). Each depositional sequence is described briefly, using the following abbreviations in both text and

figures: LST = lowstand systems tract, TST = transgressive systems tract, HST = highstand systems tract.

Lekhwair Synthem: the uppermost part of the formation consists of mud- and wacke-stones with aragonitic foraminifers (*Hensonina* and high spired *Trocholina*) and algae (*Cylindroporella*, *Salpingoporella*, *Acroporella* (?), *Terquemella*, *Carpathoporella*, *Permocalculus*,...), as well as non-aragonitic forms such as *Choffatella* (foraminifer) and *Hensonella* (alga). This "aragonitic algal debris facies" is characteristic of an inner platform depositional environment.

The top of the Lekhwair Synthem is marked by a bored hard-ground (Fig. 8-9). It exhibits strong early diagenesis including an early episode of lithification that occurred after a burrowing stage and before a boring stage. This event may have been accompanied by minor subaerial exposure as indicated by an early leaching of aragonitic bioclasts, with the resulting voids later filled by sediments.

The **Kharaib Synthem** is subdivided into 4 cycles, namely, Kharaib-1, 2, 3 and 4.

Kharaib 1: The cycle starts with a very thin transgressive layer (4 ft) of mud-dominated fine-grained packstones, commonly partly dolomitized and locally with sparse quartz silts. The remaining part of this cycle (45 ft) though rather homogenous displays a clear trend of upward shallowing. Its facies consists of wackestones and mud-dominated packstones with foraminifera (high spired *Trocholina*, *Chrysalidina*, *Hensonina*, orbitolinids including *Eopalorbitolina transiens* (CHERCHI et SCHROEDER 1999[a]) and primitive forms of *Palorbitolina lenticularis* (BLUMENBACH) associated with *Montseciella arabica* (HENSON) [in the upper half] and algae (*Hensonella*, *Montiella*, *Cylindroporella*, *Carpathoporella*, *Permocalculus*). Such a facies is characteristic of an inner-ramp setting, probably shallower (absence of *Choffatella*) than the "algal debris facies" found in the Lekhwair Synthem.

The top of the Kharaib 1 cycle is marked by a bored hard-ground, commonly masked by large stylolites associated with the change in texture. At the scale of the field study there is no clear evidence of subaerial exposure.

Kharaib 2: The cycle starts with a transgressive interval consisting of an extremely thin parasequence (2 ft) followed by a thin one (7.5 ft). They are topped by very thin marls sometimes with a coquina at the base. The dominant facies of the cycle are similar to those of the underlying Kharaib 1 HST except for the notable abundance of *Choffatella* and orbitolinids (*Eopalorbitolina transiens* and primitive forms of *Palorbitolina lenticularis*)

which records a flooding event, a characteristic of a mid-ramp environment. The remaining part of the cycle (HST) may be subdivided into two slightly regressive parasequences (19.5 ft and 30.5 ft). They are argillaceous mud- and wacke-stones, often slightly dolomitic, with *Lenticulina* and *Choffatella*, i.e. an association indicative of a deep- (outer-) ramp setting.

The top of the Kharaib 2 cycle is marked by a burrowed firm-ground. According to micropaleontological investigations carried out over the rather small area studied, we cannot exclude a downward shift of facies from a deep- (outer-) ramp setting below to a mid-ramp setting above.

Kharaib 3: The cycle consists of a thin TST (10 ft) followed by a thick HST (88.5 ft). The transgressive part of the cycle can be split into 3 very thin parasequences, each of which has an orbitolinid-rich lag at its base. The flooding events are marly layers with abundant typical forms of *Palorbitolina lenticularis* and common *Choffatella* and *Lenticulina*. If one accepts the hypothesis of a downward shift, one or two of the three parasequences ascribed to the TST should be referred to a LST. Though the regressive part of the cycle is reasonably homogenous it shows a distinct shallowing upward trend. Facies are rather similar to those found in the Kharaib 1 HST; they consist of wackestones and mud-dominated packstones with foraminifera (low-spired *Trocholina*, *Chrysalidina*, *Hensonina* and orbitolinids including typical forms of *Palorbitolina lenticularis* associated with *Montseciella arabica* (Fig. 12) at the base) and algae (*Hensonella*, *Cylindroporella*, *Carpathoporella*, *Permocalculus*). They characterize mid-ramp environments.

The Kharaib 3 cycle terminates in a discrete erosional surface commonly masked by the stylolites developed at the change in lithologic textures.

Kharaib 4: The cycle consists of a thin TST (7.5 ft) followed by a relatively thick HST (34.5 ft). The transgressive portion is characterized by alternations of grain-dominated packstones and mud-dominated wacke- or pack- stones. Such textural alternations have led to the growth of stylolites. The regressive part, the thickness of which varies considerably from one well to another, displays a net shallowing upward trend. In some cases, marly layers with corals are found toward the top of this cycle. Facies

are similar to those found in Kharaib 1 HST or Kharaib 3 HST; they consist of wackestones and mud-dominated packstones with foraminifera (low-spired *Trocholina*, *Chrysalidina*, *Hensonina* and orbitolinids including typical forms of *Palorbitolina lenticularis*) and algae (*Hensonella*, *Cylindroporella*, *Carpathoporella*, *Permocalculus*). Environments grade from a mid-ramp setting at the base to an inner- or even innermost- ramp setting near the top.

The top of the Kharaib 4 cycle is marked by a karst surface or by an erosional surface that is commonly masked by stylolites developed in association with the change in texture.

The **Hawar Synthem** comprises only one cycle and can be recognized easily on the Gamma-Ray log.

The Hawar cycle reflects the flooding of the exposed "Kharaib" platform. It can be split into a rather thick TST (21.5 ft) and a thin HST (6.5 ft). The transgressive interval consists of a set of thin, shallowing upward parasequences topped by firm-grounds; the final sequence of the set is glauconite-rich. At its base is a transgressive lag deposit consisting of a very thin layer of float- to grain- stones with small lithoclasts reworked from the underlying unit. It is succeeded by very well sorted fine-grained grainstones, locally cross-bedded or with features such as keystone vugs, indicative of foreshore to upper shoreface (coastal) settings. The succeeding dominant facies is mud-dominated pack- and wacke-stones with abundant orbitolinids (typical and advanced forms of *Palorbitolina lenticularis*: Fig. 10-11); it could be called an orbitolinid floatstone. These foraminifera are found associated with *Choffatella* and *Lenticulina*. Such an unusual association suggests reworking in lower shoreface to offshore (outer-ramp) sediments in a storm-dominated setting. The regressive part of the cycle is represented by a thin shale layer (with some quartz silt) easily identified on the Neutron Porosity log. At the bottom of this interval, a thin layer of orbitolinid floatstone with a mudstone to marl matrix indicates condensation.

The top of the Hawar cycle is an irregular (burrowed) surface at the contact between the shale layer below and limestones above. According to our micropaleontological investigations, there is a significant downward shift of facies from an outer-ramp setting below to an innermost ramp setting above.

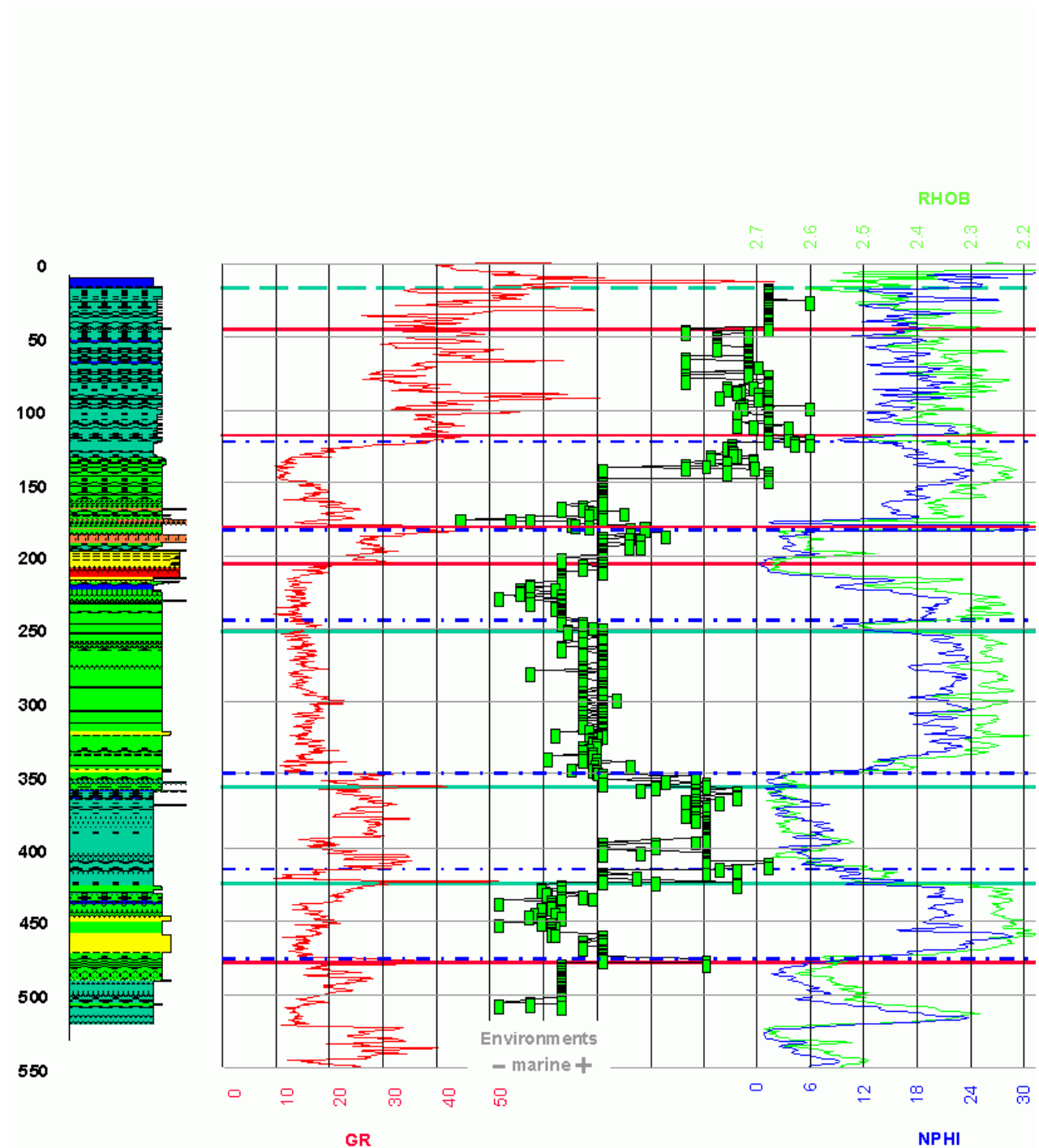
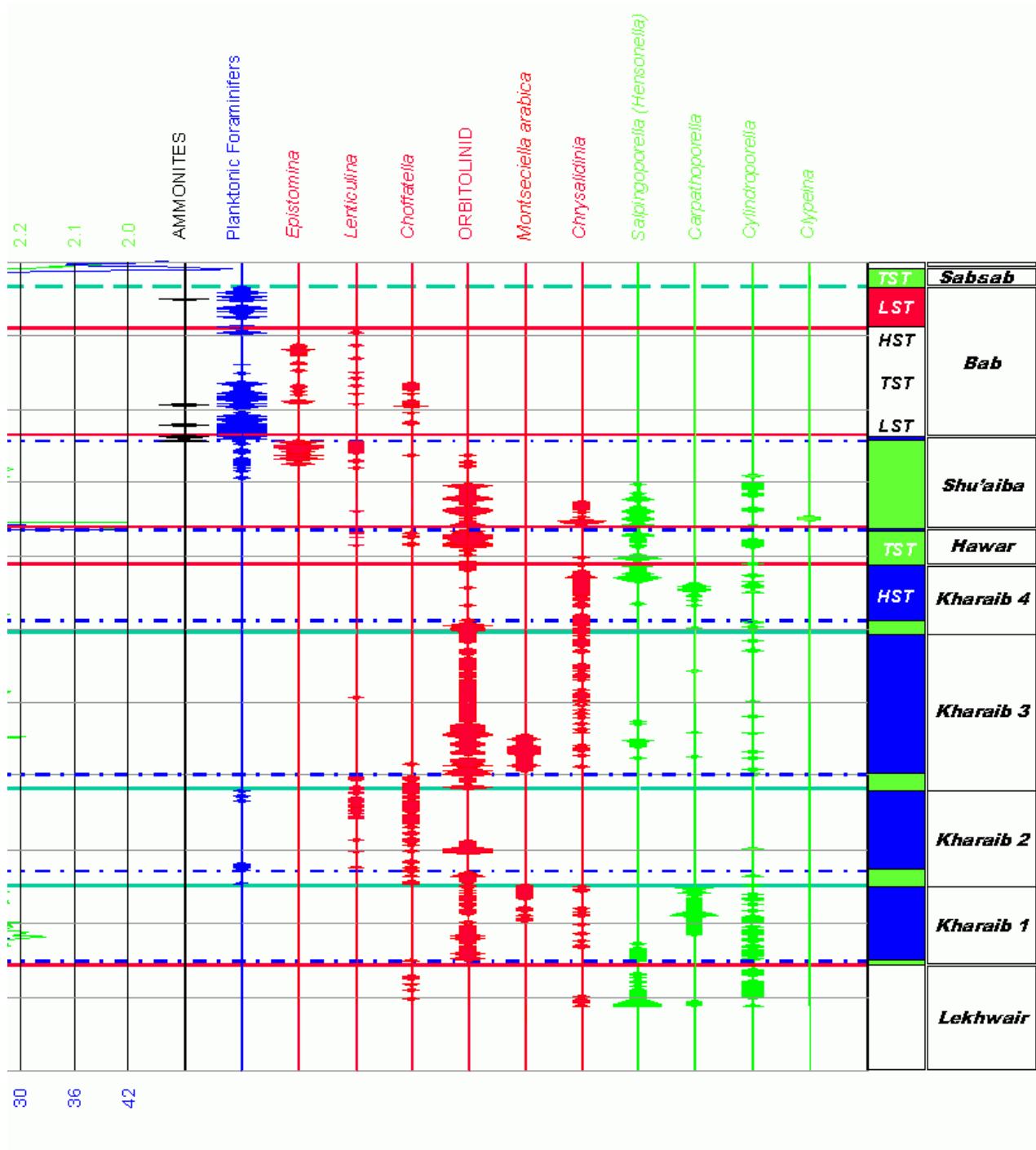


Figure 7: Stratigraphic subdivision of the upper part of the so-called "Thamama" in the reference well of field "A" (from left to right: Gamma Ray = red log, Environments = green squares, reversed NPHI = blue log, reversed RHOB = green log, distribution of the main fossils, third order sequences, allostratigraphic units). This figure illustrates how paleontological data may be used to identify (and quantify) transgressive and regressive trends. Some fossils were chosen as index fossils: they were given an index value and their occurrence was semi-quantified (missing, rare, common, abundant). The weighted average was then computed for their association in each sample. This technique, similar to that developed by BOISSEAU, DUPONT and MUSSARD (1990), is not straightforward since its use requires hypotheses (which species are the index fossils and what importance should be ascribed them) and a series of iterative tests in order to obtain the best (potentially most nearly valid) interpretation.



The **Shu'aiba Syntem** (51 ft) starts with three thin, shallowing-upward parasequences. Each parasequence comprises *Palorbitolina* wackestones at the base, and microbial boundstones (*Bacinella* structures, *Gakhumella*, coccoid and filamentous structures) with some algae (*Clypeina ummshaifensis* GRANIER 2002, *Gyroporella lukicae* SOKAČ et VELIĆ, *Salpingoporella (Hensonella) dinarica* RADOIČIĆ) at the top. The remainder of the unit consists predominantly of mud- and wacke-stones with *Cuneolina* and rare *Palorbitolina lenticularis*,

then *Choffatella*, then *Lenticulina* and common *Epistomina* associated with planktonic foraminifera, including *Hedbergella infracretacea* (GLAESNER). The uppermost part of the unit (2 ft) is a condensed section. In the reference well, it consists of two nodular beds with ammonites (Fig. 13). As shown by microfossil and facies assemblages, most of the unit showed a general deepening upward, from inner-ramp to outermost ramp and even to a basinal setting. Sedimentation could not accommodate to ("catch up" with) the relatively high rate of subsidence. This major change in

regional epeirogeny began possibly at the Hawar - Shu'aiba boundary, or earlier at the Kharai - Hawar boundary.

There is no clear evidence of subaerial exposure at the base of the Shu'aiba Formation but there is also no evidence that it was not so exposed. The stacking pattern of the three shallowing-upward parasequences in the lowermost part of the Shu'aiba are retrogradational: the boundstone facies thin progressively upward from one parasequence to the next. This suggests either: - that there was exposure, so that sedimentation records the sole TST in the area studied (the interpretation we favour); - or that there was no exposure and the first shallowing-upward parasequence may represent the LST.



Figure 8: Scan of polished core (slab). Hard-ground marking the Lekhwair-Kharai boundary in well N° 12.

One of us (R.B.) identified *Chelonicer* sp., *Epicheloniceras* sp., *Valdedorsella* sp., and *Gargasicer* sp. that point toward a Middle Aptian (Gargasian) age for the condensed section (HST).

The **Bab Synthem** (93 ft) is also ammonite-bearing (Fig. 14). Microfossils are sparsely scattered foraminifera (*Choffatella*, *Lenticulina* - Fig. 15-16 - and *Epistomina*). Palaeontological associations and facies indicate rather deep to shallower basinal environments. Lithofacies are predominantly organic-rich *Nannoconus* oozes - "chalks" - with planktonic foraminifera, including *Hedbergella infracretacea* (GLAESNER) (Fig. 17), and subordinate mud-dominated fabrics (including Gastropod floatstones).



Figure 9: Scan of polished core (slab). Hard-ground marking the Lekhwair-Kharai boundary in well N° 19.

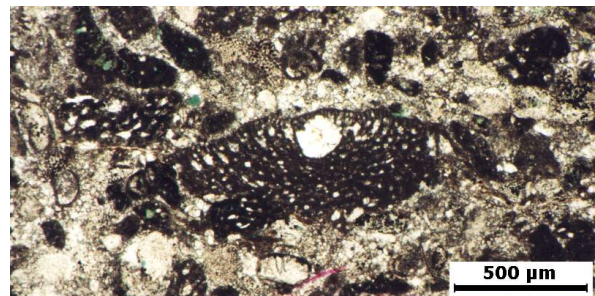


Figure 10: Thin section photograph. *Palorbitolina lenticularis* (axial section), along with the occurrence of glauconite. Hawar (TST) in well N° 14.

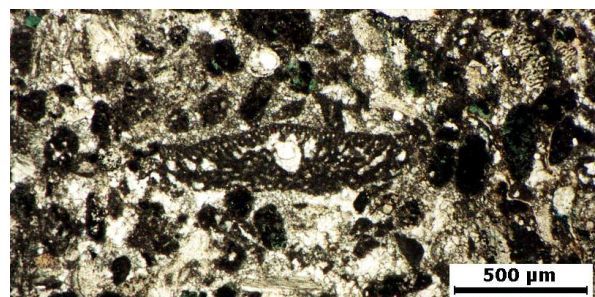


Figure 11: Thin section photograph. *Palorbitolina lenticularis* (axial section), along with the occurrence of glauconite. Hawar (TST) in well N° 14.

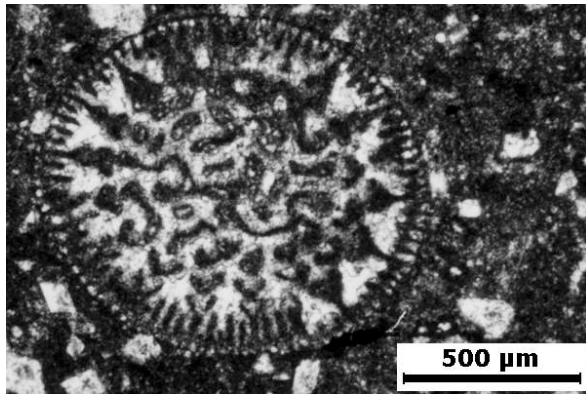


Figure 12: Thin section photograph. *Montseciella arabica* (somewhat oblique transverse section). Kharaib (HST 3) in well N° 21.



Figure 13: Photograph of polished core (slab). Ammonites. Shu'aiba (condensed section = HST) in ADMA well N° 4 of field "B", offshore Abu Dhabi.

Chalk facies predominate both at the base and at the top of the interval. On a regional scale, these "sapropelic" deposits were formed in a tongue of the Tethyan ocean bounded by exposed relict Shu'aiba platforms; starvation in lowstand settings favored the deposition and preservation of these organic-rich facies.

One of us (R.B.) identified *Chelonicerias* sp., *Epicheloniceras* sp., and *Colombiceras* sp. These Ammonite occurrences also suggest a Middle Aptian (Gargasian) age for this unit.

In field "A", this uppermost unit of the so-called "Thamama Group" is separated from the overlying formation by a firm-ground at the top of the uppermost limestone bed.

Interpretations and perspective

Standard chronostratigraphy

A more precise biostratigraphic dating may be possible based on a new evaluation of the orbitolinids by one of us (R.S.) that permits a comparison with the well-known Urgonian limestones of southeastern France and western Switzerland (CHAROLLAIS *et alii*, 1992; CLAVEL *et alii*, 2002; SCHROEDER *et alii*, 2002). These fossils suggest (Fig. 7) that:

- The top of the Lekhwair Synthem may be of Early Barremian age (or older);
- The Kharaib 1 cycle with *Eopalorbitolina transiens*, *Montseciella arabica*, and primitive forms of *Palorbitolina lenticularis* (*P. gr. lenticularis*) appears to be the equivalent of Urgonian cycle Barremian 3 as defined by CHAROLLAIS *et alii* (1992). It may correspond to the basal Upper Barremian ;

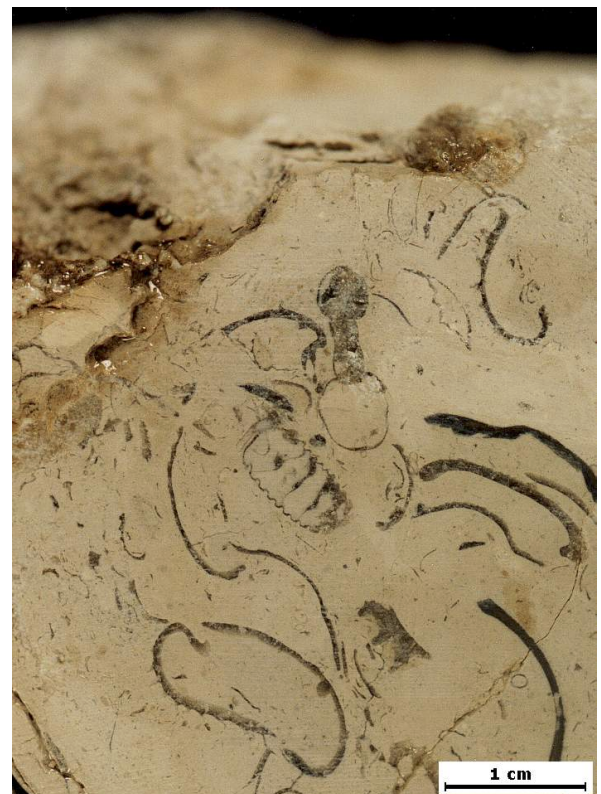


Figure 14: Photograph of polished core (slab). Ammonites. Bab (TST 1) in well N° 14.

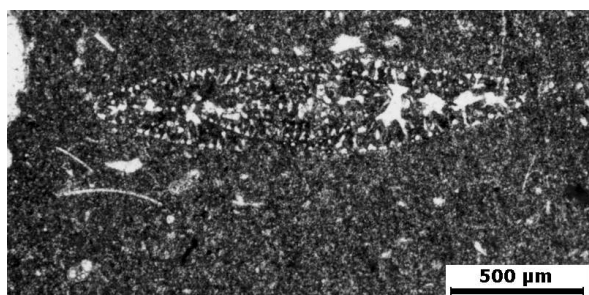


Figure 15: Thin section photograph. *Choffatella decipiens* (subaxial section), along with planktonic foraminifera. Bab (LST 1) in well N° 21.

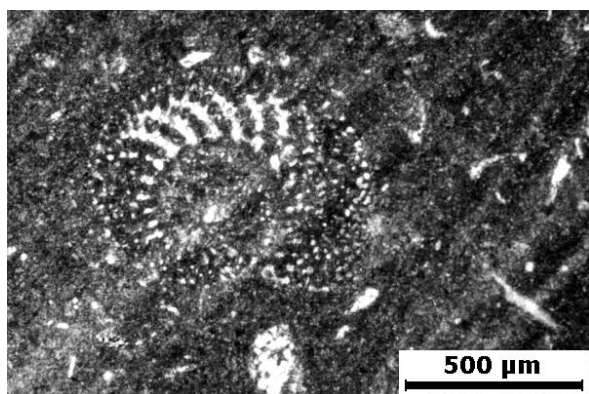


Figure 16: Thin section photograph. *Choffatella decipiens* (equatorial section). Bab (LST 1) in well N° 21.

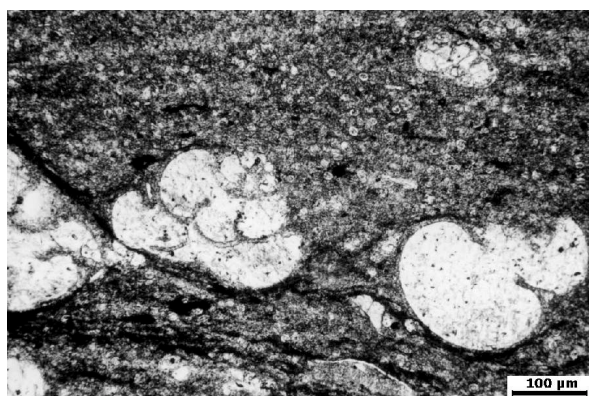


Figure 17: Thin section photograph. Planktonic foraminifera in an organic-rich *Nannoconus* ooze. Bab (LST 1) in well N° 21.

- The Kharaib 2 cycle with *Eopalorbitolina transiens* still present along with primitive forms of *Palorbitolina lenticularis* (*P. gr. lenticularis*), but lacking *Montseciella arabica*, could be of the same age as their Urgonian cycle Barremian 4;
- The Kharaib 3 cycle with typical forms of *Palorbitolina lenticularis* and *Montseciella arabica* may be the equivalent of their Urgonian cycle Barremian 5 and mark the transition from Upper Barremian to Lower Aptian;
- The Kharaib 4 cycle with typical forms of *Palorbitolina lenticularis*, but lacking *Montseciella arabica*, could equate with their Urgonian cycle Bedoulian 1;

- Therefore the Kharaib Synthem is thought to represent most of the Upper Barremian and part of the Lower Aptian;
- The Hawar cycle with typical and advanced forms of *Palorbitolina lenticularis* may correspond to their Urgonian cycle Bedoulian 2, *i.e.* to an Early Aptian (Bedoulian) age.

Key-surfaces or beds defined by their benthic assemblage

Choffatella decipiens

A significant ecological change takes place at the Lekhwair-Kharaib boundary. The foraminifer *Choffatella decipiens* in Hauterivian and possibly Early Barremian times inhabited shallow water environments in association with calcareous green algae, but in the Late Barremian and thereafter is found only in deeper environments. This change in habitat may be related to the presence of new competitors, *i.e.* representatives of the orbitolinids, and the change may be useful in discriminating the two Barremian sub-stages.

Orbitolinis

Throughout the interval discussed these foraminifera are usually present, though commonly not numerous. However there are several thin layers in which they are particularly abundant. These key beds mark flooding events usually interpreted as storm deposits and are therefore traceable over long distances. On well logs, some of these beds correspond to gamma-ray peaks as in Kharaib 3 TST and Hawar TST. In other cases, as in Kharaib 4 TST, there is no peak on the gamma-ray log but the interval can be detected from Neutron Porosity or Density logs because the slight textural variation associated with it allowed the later development of pressure-solution seams.

A conceptual model for the so-called "Shu'aiba"

The deposition of the Shu'aiba Formation in "A" field of offshore Abu Dhabi (Fig. 1) took place under basinal conditions. On the contrary, most onshore fields in Abu Dhabi (HARRIS, HAY and TWOMBLY, 1968; FROST, BLIEFNICK and HARRIS, 1983), Qatar and Oman (WITT and GÖKDAG, 1995) are in shallow-water carbonate platform settings. But the majority of the existing interpretations of stratigraphic relationships between onshore and offshore, formations are incorrect. The Bab basinal facies do not pass laterally into Shu'aiba equivalent platforms with rudists, nor do they show an onlap or offlap relationship with them. In reality, the Shu'aiba platform facies pass laterally into Shu'aiba-equivalent basinal facies; in the same way Bab basinal facies show a lateral transition into Bab-equivalent platform facies.

These revisions in correlation (Fig. 2) are based on data provided by sequence stratigraphy which, along with new biostratigraphic data, make possible a fresh comprehensive interpretation of both platform and basin sedimentation during the time interval in question. It includes three almost complete third order cycles:

1. the Shu'aiba cycle (the LST of which has not been documented in the areas studied),
2. the (older) Bab cycle,
3. the lower part of the older Nahr Umr cycle (the LST of which is the younger Bab and the TST of which is the Sabsab).

Following a forced regression at the end of the Hawar cycle, the Shu'aiba transgression allowed shallow-water carbonates to re-establish in proximal areas. Microbes (*Bacinella* structures) flourished locally; their growth was sufficient to "keep up" with a rise in relative sea-level in some areas while in slightly deeper areas basinal sedimentation began.

The Shu'aiba HST interval saw the development of various carbonate platforms, either isolated or not, with rudistid colonies developed over some relative highs while in the intra-shelf basin the equivalent section is often condensed.

The older Bab cycle, began with a forced regression. The Shu'aiba platforms were exposed and karstified. A new generation of rudist buildups developed either down-stepping from stranded Shu'aiba escarpments (thus typical "grafted" platforms: Fig. 18, elsewhere erroneously termed "Shu'aiba clinoforms" (Fig. 19): CALAVAN *et alii*, 1992; FITCHEN, 1997) or on relative highs in the basin possibly formed by

movement of Palaeozoic salt (Fig. 21). At this time, intra-shelf basins, although probably still in communication with the Tethyan ocean, began to become isolated and starved, thus causing the deposition of organic-rich sediments at the base of the (older) Bab. Organic content decreased upward with the subsequent rise in relative sea-level. There were at least two of these intrashelf basins, one south of the Qatar arch that extended as far as the United Arab Emirates and reached Oman, and one north of the Qatar arch that included Bahrain and peripheral portions of Saudi Arabia and Iraq.

The next cycle, *i.e.* the older Nahr Umr cycle, also began with a forced regression. Once again platforms of both the Shu'aiba and the (older) Bab were exposed and partially karstified. A third generation of buildups appeared either as downsteps from fossil (older) Bab escarpments, or on relative highs in the basin. It was at this time that the organic-rich sediments near the top of the (younger) Bab were deposited.

Orbitolinid accumulations, a characteristic of the Sabsab facies, formed basinal onlapping wedges (*i.e.* healing phase wedges, off-break wedges, or flexure wedges) on the margins of both the Bab and Shu'aiba platforms (Fig. 6), that shed as they were being drowned by the coeval wide-spread (older) Nahr Umr transgression. The Sabsab forms a rather thin lag deposit (Fig. 5) above the platform facies (either Shu'aiba or Bab); it may be absent at the edges of the platforms, *i.e.* in a more or less narrow by-pass area; at the foot of the platform slopes it commonly built a rather thick wedge that thinned rapidly basinward as the series became condensed.

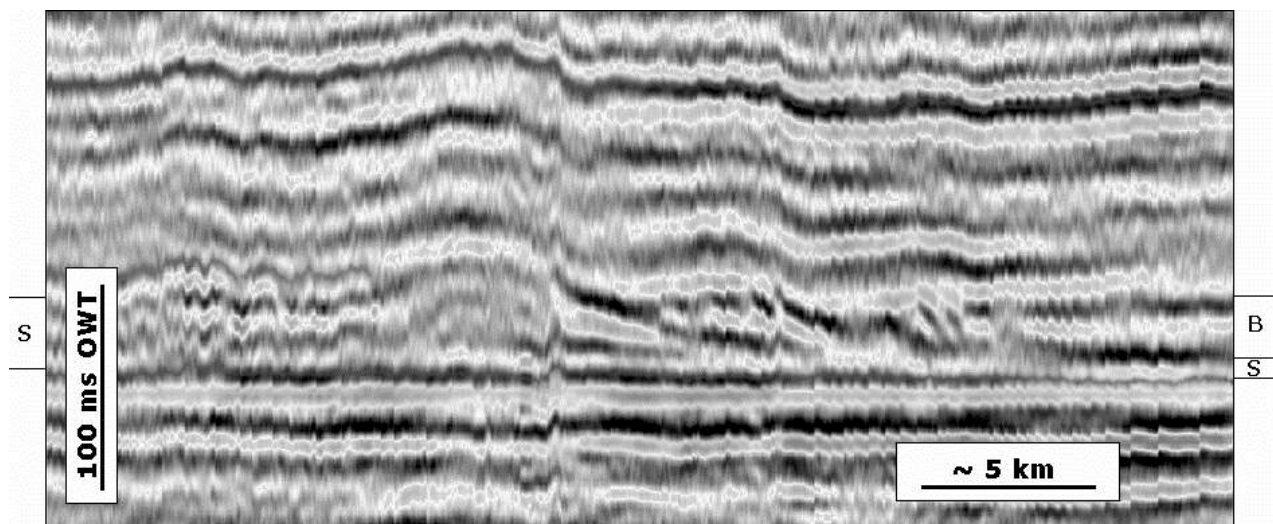


Figure 18: Seismic section (flattened on Top Hawar) from onshore Abu Dhabi illustrating the platform (left) to basin (right) transition in the Shu'aiba-Bab-Sabsab interval (S = Shu'aiba; B = Bab).

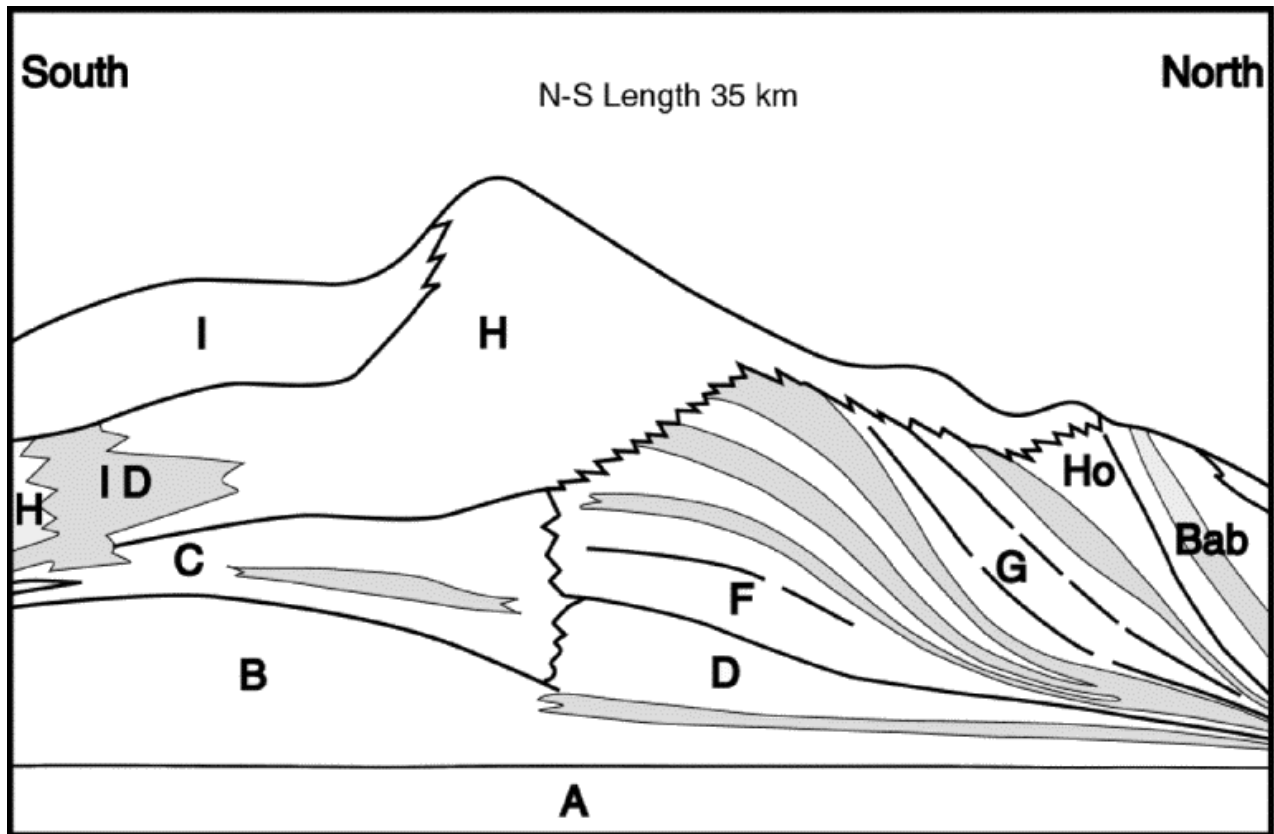


Figure 19: Distribution of reservoirs (white) and barriers (light grey) in the Bu Hasa field, onshore Abu Dhabi as interpreted by HARRIS, HAY and TWOMBLY (1968) and modified by HULSTRAND, ABOU CHOUBA and AL BAKER (1985).

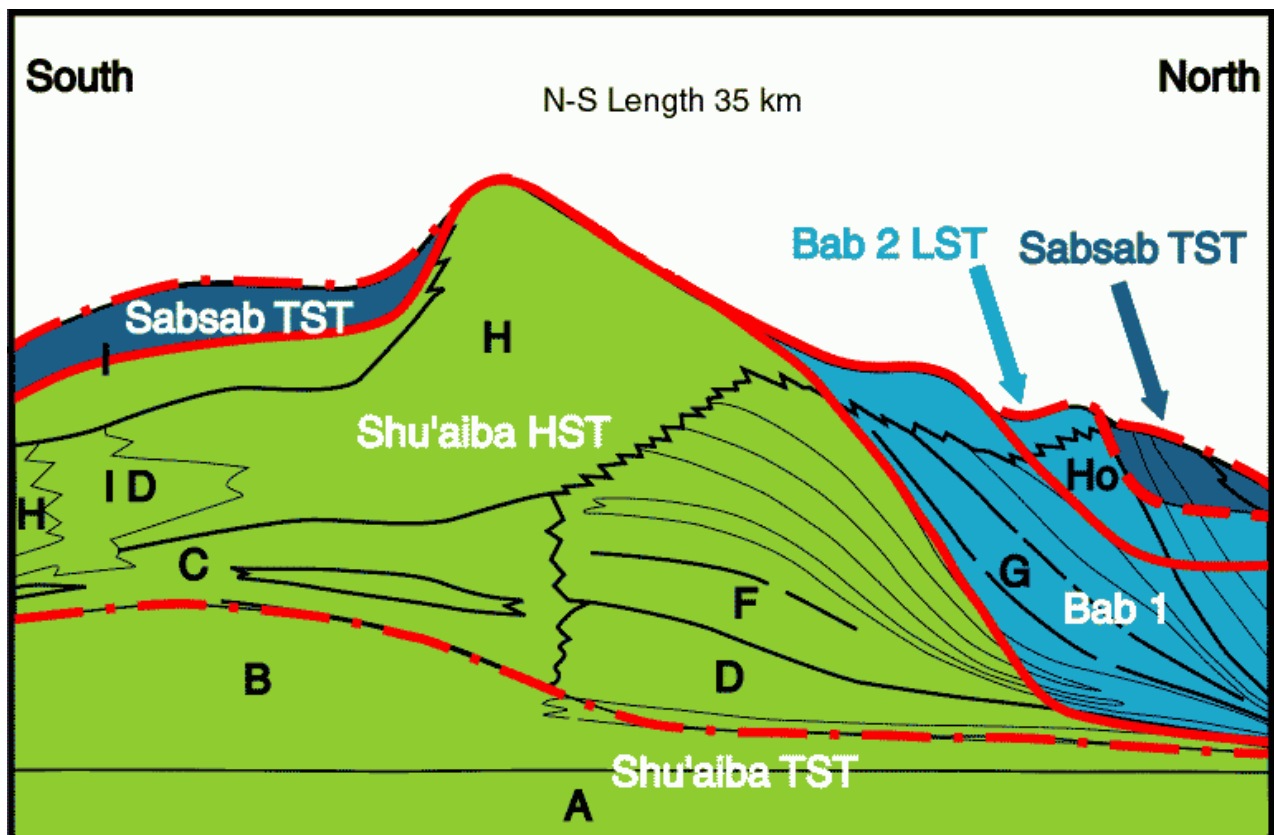


Figure 20: Tentative re-interpretation of the stratigraphical relationships of Fig. 19 based on the current study (time-lines in red).

KENNEDY and SIMMONS (1991) reported an ammonite association with *Knemiceras* in Jebel Madar, Oman, some 50 meters above the base of the Nahr Umr Formation dating it as late Early to early Middle Albian. On the basis of our new ammonite findings the Nahr Umr transgression is not of Early Albian age as stated by previous authors but must be dated as Middle Aptian.

Conclusions

The new interpretation of the lithologic and faunal succession in the upper part of the so-called "Thamama Group" in field "A" using allo- and sequence stratigraphy (Fig. 7) shows that:

- The Kharaiib Synthem (about 250 ft thick in the reference well) can be split into four third order cycles, from bottom to

- top: Kharaiib 1 to 4;
- Both the Hawar and the Shu'aiba Synthems which are relatively thin (respectively 27 ft and 53 ft) represent one cycle each;
- The Bab Synthem (that attains a thickness of 93 ft in the reference well) includes one cycle and the beginning of the next one, i.e. the LST preceding the generalized Nahr Umr transgression. As such the Bab Synthem is genetically related to the Nahr Umr and consequently it should be transferred to the Wasi'a Supersynthem (pro "Group").

This new stratigraphic model documents explicitly the geometric relations between the Shu'aiba and the Bab platforms (Fig. 20-21) thus permitting recognition of the significance of these relationships for petroleum geology with special emphasis on reservoir geometries and characteristics.

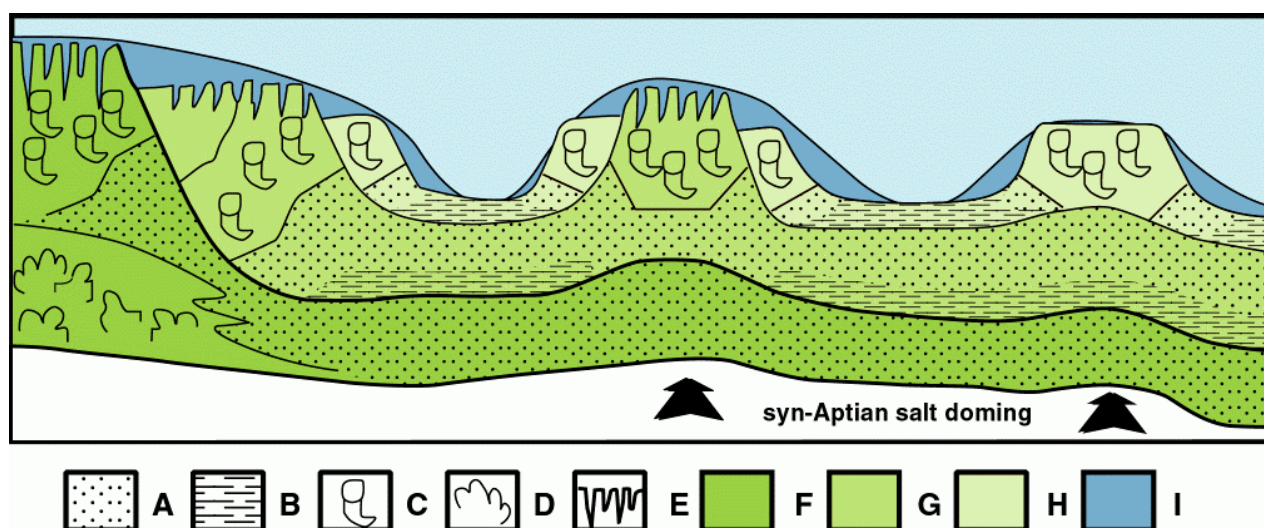


Figure 21: Sketch summarizing the Middle Aptian regional basin history (from GRANIER (2000), modified). This figure illustrates the various platform-basin relationships during the Shu'aiba, Bab and Sabsab times (A = basin facies; B = organic-rich oozes (Bab LST 1 and 2); C = rudist facies; D = *Bacinnella* facies build-ups (Shu'aiba TST); E = karst surface; F = Shu'aiba; G = Bab 1; H = Bab 2; I = Sabsab).

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